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Characterization of a Diverging Cusped Field Thruster Operating on Krypton

67th Gaseous Electronics Conference

Tuesday, November 4, 2014

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Outline

- **Motivation for using krypton**
- **Diverging Cusped Field Thruster (DCFT)**
  - Operation on krypton vs. xenon
  - Frequency characteristics
- **Krypton Laser Induced Fluorescence (LIF)**
  - Time-Averaged LIF Velocimetry
  - Time-Synchronized LIF Velocimetry
- **Summary and continuing work**

Motivation for Using Krypton

- **Xenon has been expensive recently**
  - Prices peaked at $40 per std liter
  - Increasing industrial use, scarcity
  - ~50,000 liters per GEO comsat
  - 200-500k liters for SOTV…
- **Krypton less expensive**
  - 1/10 cost per volume, 1/6 by mass
  - 150% tankage required (vs Xe)
  - GEO comsat savings

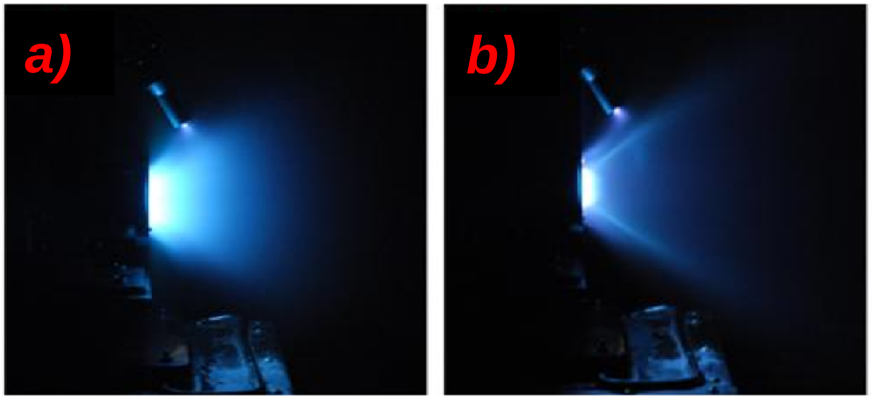
Property	Units	Xe	Kr
Atomic Mass	amu	131.3	83.8
1^{st} Ionization Energy	eV	12.1	14.0
2^{nd} Ionization Energy	eV	21	24
3^{rd} Ionization Energy	eV	32	37
Atmospheric Concentration	ppb	87	1000
Stable Isotopes		9	6
Odd Isotopes		2	1
Critical Pressure	MPa	5.84	5.50
Critical Temperature	K	290	209
Boiling Point (1 atm)	K	161	120

- **Krypton Similar to Xenon**
  - Noble gases
  - Similar physical properties
  - Electrons bound more tightly
    - Less electron shielding
    - Higher ionization energies, +15%
  - More ideal gas behavior
    - Less compressible
    - More difficult pressurized storage
    - 150% tankage required for Kr (vs Xe)
- **Kr is nearly a “drop in” replacement for Xe**
  - Some loss in efficiency
    - 25% gain in Isp (vs Xe)
    - 80% thrust (vs Xe)
    - Advantageous for station keeping
  - No changes required to thruster
  - Minimal changes required to propellant management
  - No increased likelihood of S/C contamination

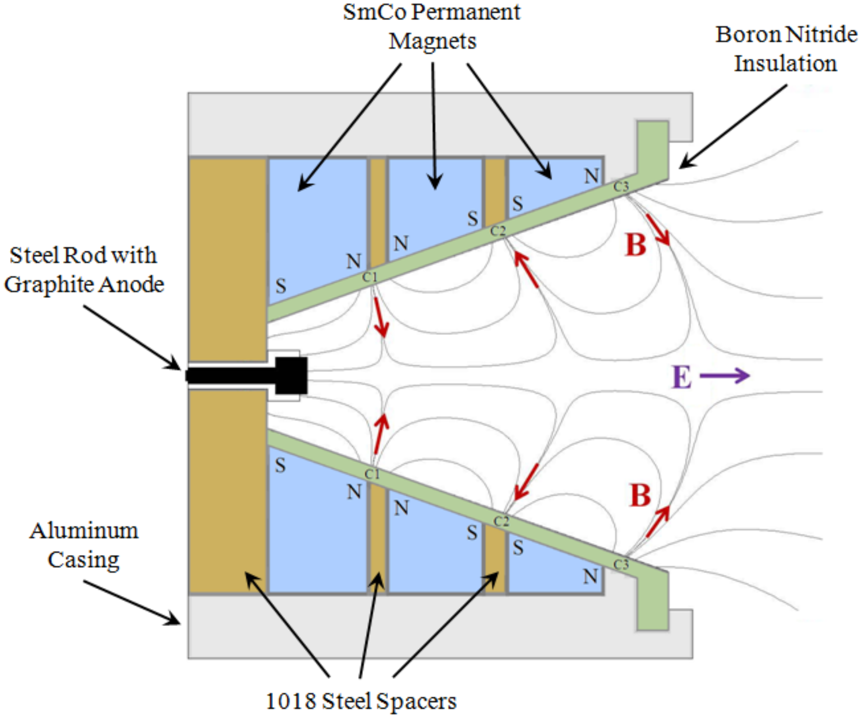
Diverging Cusped Field Thruster

Two, distinct operating modes:

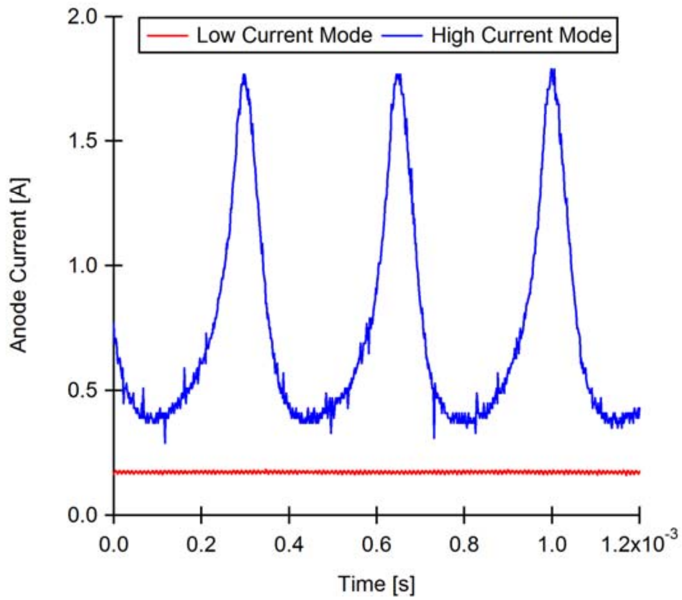
- **Low Current Mode**
  - Quiescent, time averaged measurements are relevant
- **High current mode with**
  - *Strong*, quasi-periodic discharge current oscillations
  - Fluctuations in position of ionization and acceleration regions
  - Dynamics not resolved with time averaged measurements



DCFT operating in: a) High current mode, b) Low current mode



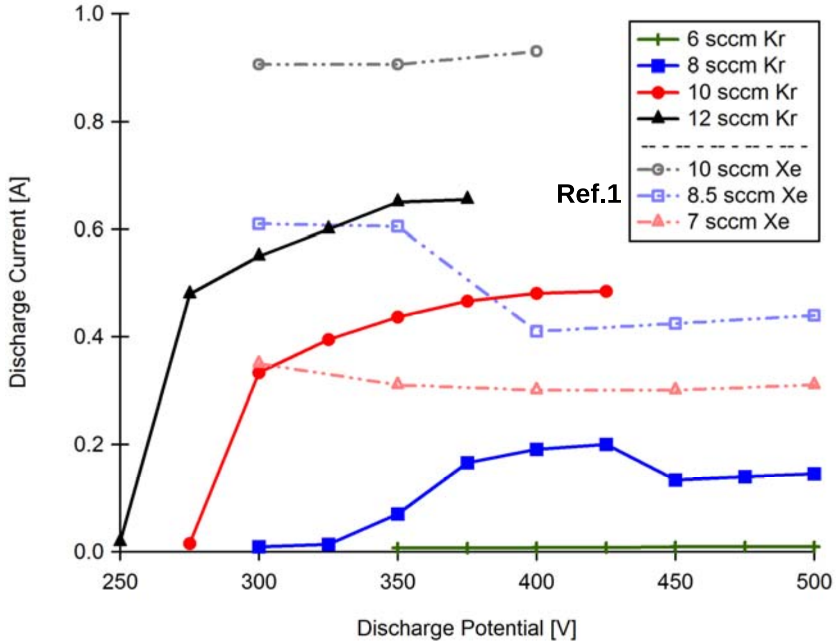
Schematic of DCFT

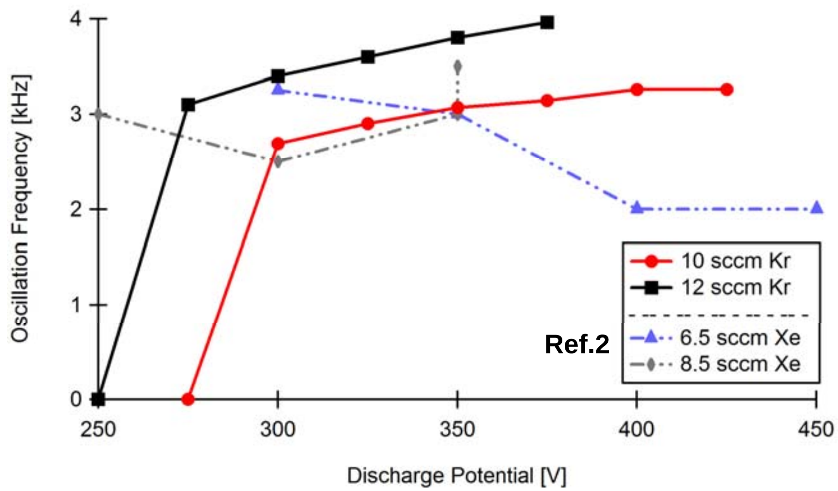


DCFT Current Traces

DCFT Operation on Krypton vs Xenon

- **Current-Voltage Characteristics**
  - Kr able to operate in ultra-low current glow mode, not sustainable in Xe
  - Kr does not roll off into low current mode at high voltage – stays oscillatory
- **Krypton**
  - Strong correlation between flow rate and frequency
  - Linear change in frequency with increased voltage
- **Xenon**
  - Little to no trend in frequency vs. voltage
  - Strong linear trend in flow rate vs. frequency



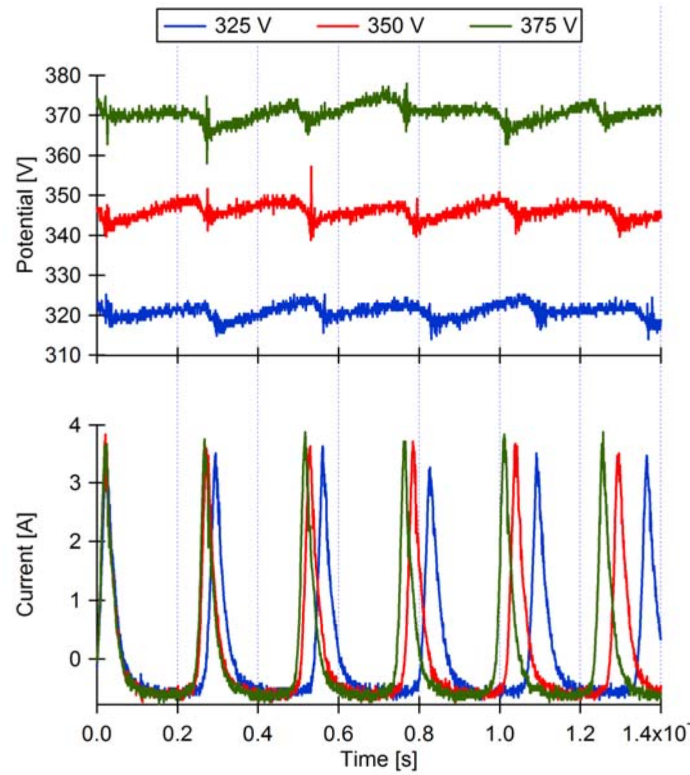


Ref. 1: Gildea, S. R., Matlock, T. S., Lozano, P., and Martínez-Sánchez, M., "Low-Frequency Oscillations in the Diverging Cusped-Field Thruster," AIAA Paper 2010-7014, 2010.

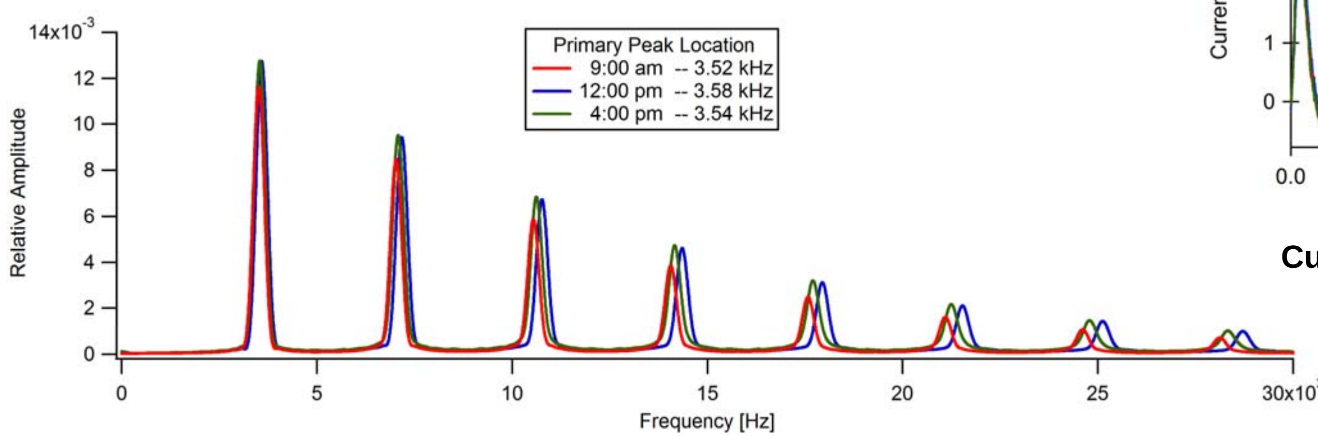
Ref. 2: Courtney, D. G., "Development and Characterization of a Diverging Cusped Field Thruster and a Lanthanum Hexaboride Hollow Cathode," S.M. Thesis, Massachusetts Inst. of Technology, Cambridge, MA, June 2008.

DCFT Frequency Characteristics

- **Operation at 12 sccm Kr**
  - Amplitude and frequency of current oscillations increase with voltage
  - Small dips in discharge voltage corresponding to current peaks
  - Voltage dips also seen in Xe operation
- **FFTs of current signal**
  - Frequency lower at start up
  - Relatively stable after 30 min, slight decrease over course of day



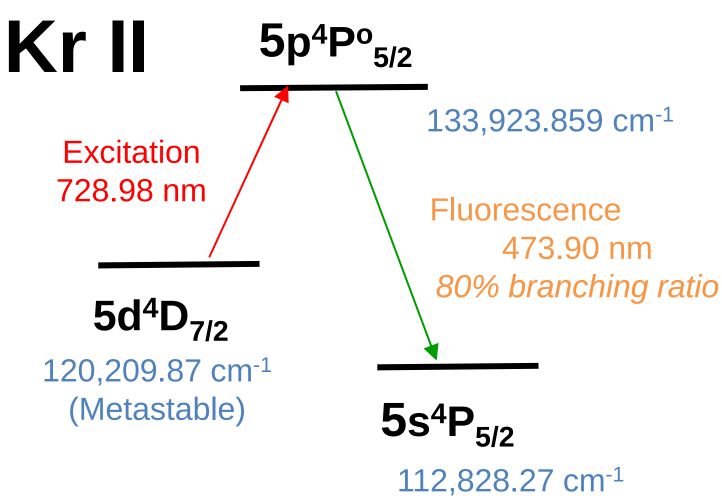
Current and voltage traces of DCFT operating on 12 sccm Kr

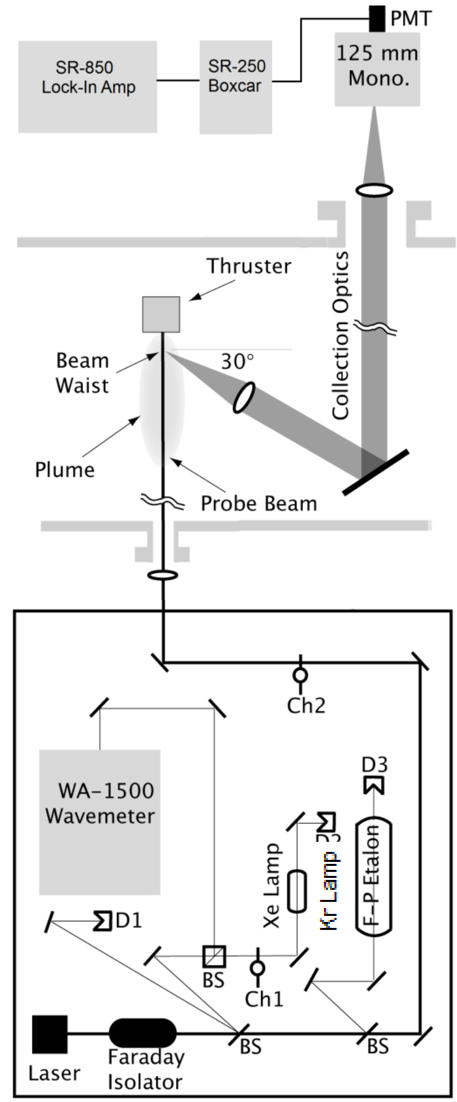


FFT of current signal at various times throughout the day
DCFT operating at 12 sccm Kr, 350 V, 0.595 A

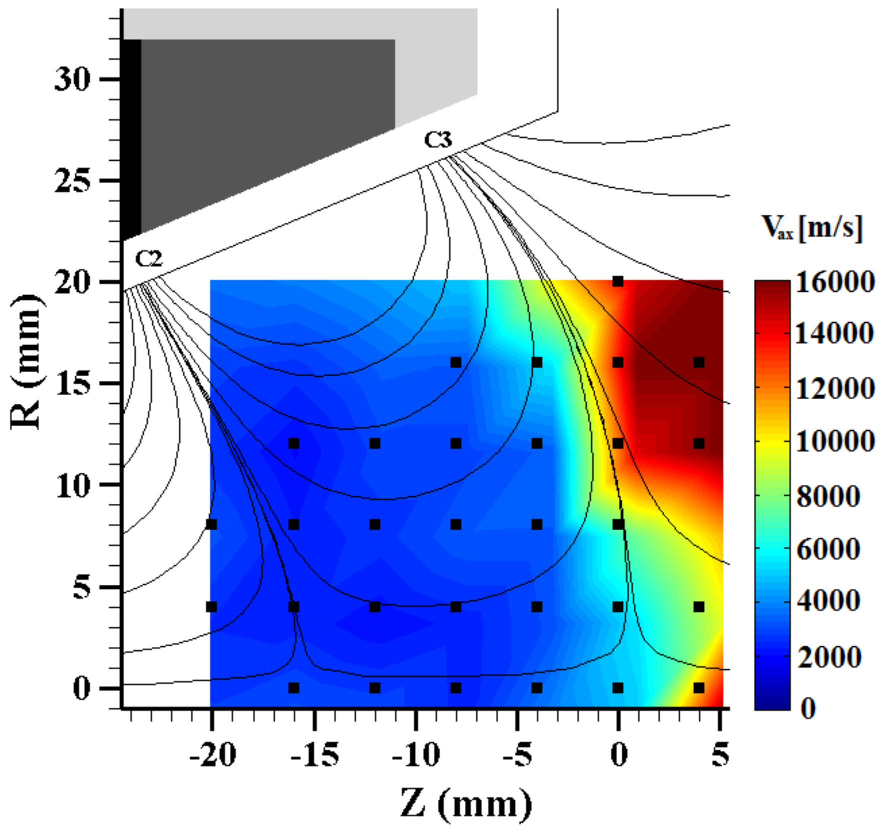
Krypton
Laser Induced Fluorescence

- **Used to measure krypton ion velocities**
  - Kr II transition, $5d^4D_{7/2}–5p^4P^\circ_{5/2}$
  - Wavelength = 728.98 nm
  - Non-resonant fluorescence with ~80% branching ratio at 473.90 nm
  - Metastable lower electronic state
  - Well characterized, hyperfine constants measured

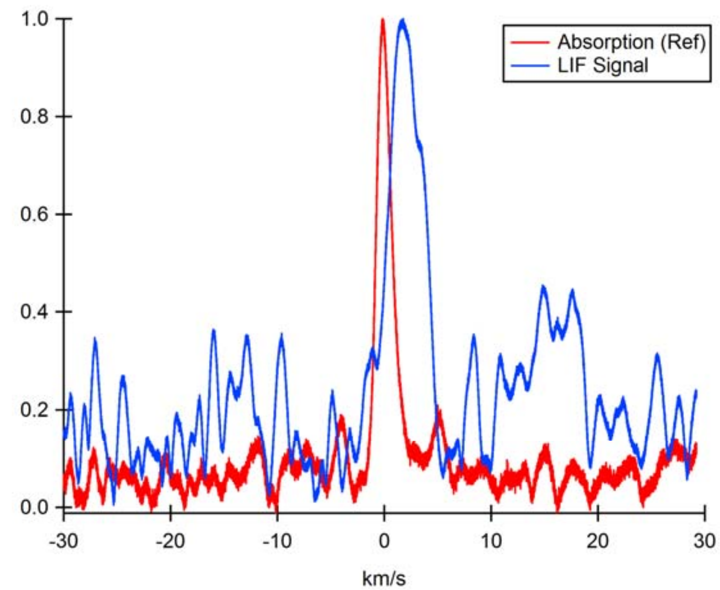




Time-Ave Axial Velocities



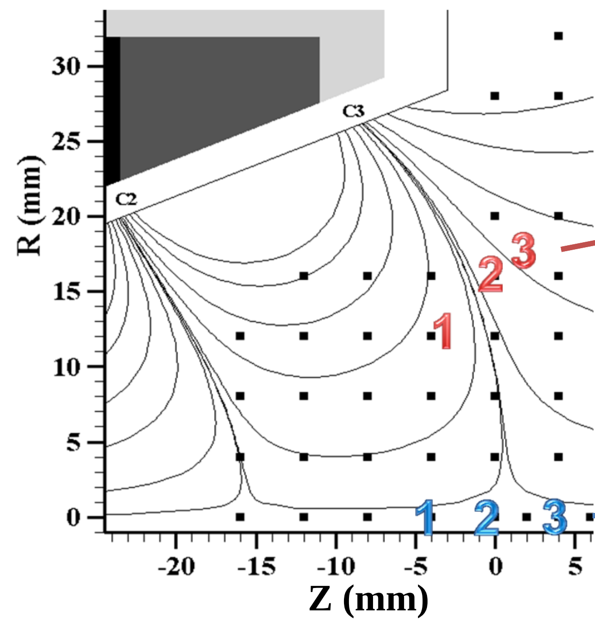
DCFT Operating on 12 sccm Kr



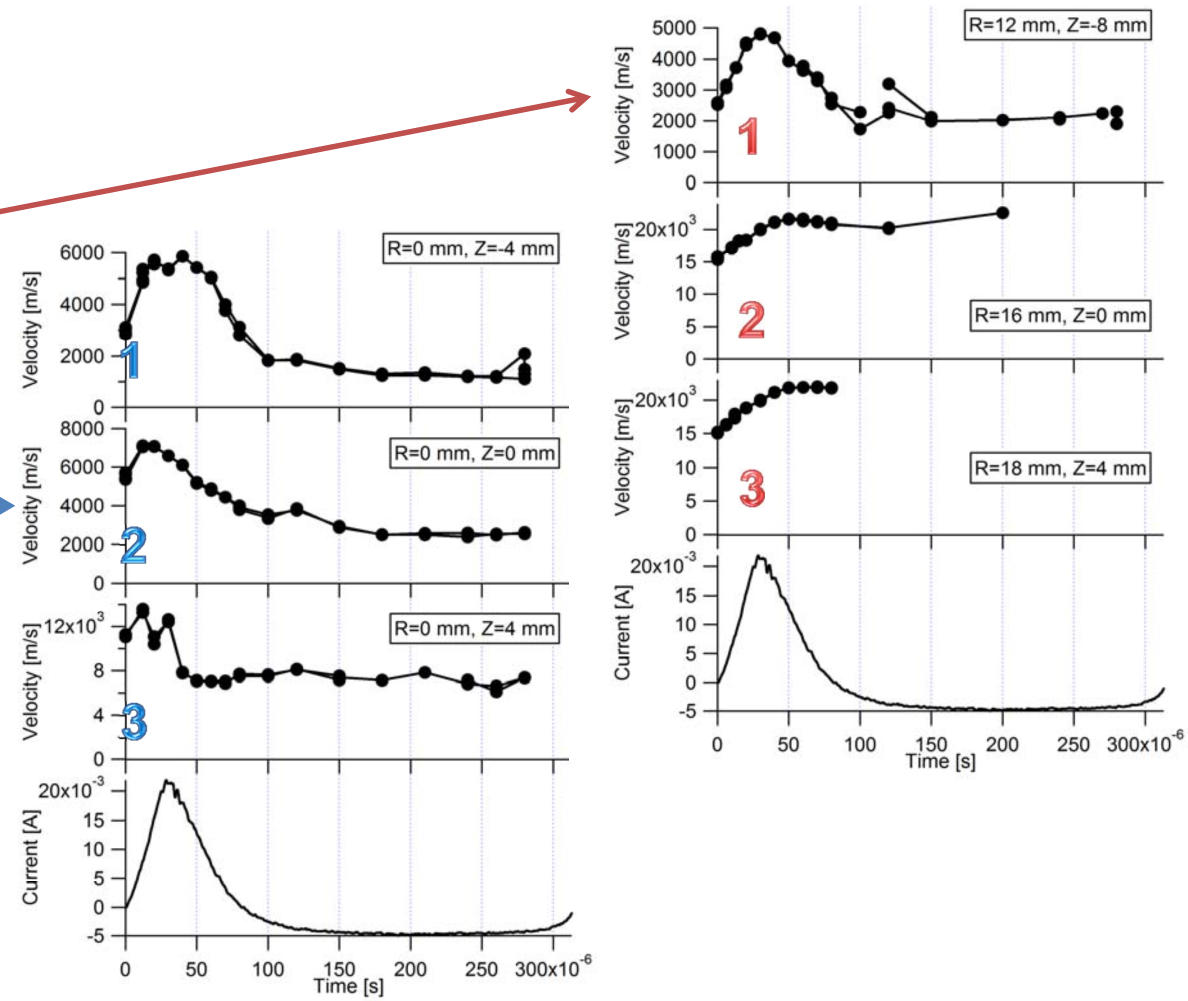
Example LIF Trace (R = 8 mm, Z = -16 mm)

DCFT Operating Conditions	
Anode Flow Rate:	12 sccm Kr
Anode Potential:	350 V
Anode Current:	0.595 A
Background Pressure:	1.2×10^{-5} torr

Time-Sync Axial Velocities



Measurement locations for time-sync LIF on DCFT



Journal article in progress: C. V. Young, N. A. MacDonald, M. A. Cappelli and W. A. Hargus, Jr. "Time-synchronized ion velocimetry of a diverging cusped field thruster operating on krypton" Physics of Plasmas (pre-print)

Summary

Summary

- **Characterization of DCFT operating on krypton**
  - Linear changes in flow rate, voltage
  - Amplitude and frequency of current oscillations increase with voltage
- **Time resolved laser-induced fluorescence**
  - Phase synchronization to breathing mode periodicity

Continuing Work

- **Extensive krypton time-sync LIF measurements made on DCFT**
  - Collaboration with Stanford University (Chris Young)
  - Data reduction nearing completion
  - Journal article in progress: "**Time-synchronized ion velocimetry of a diverging cusped field thruster operating on krypton**" Physics of Plasmas (pre-print)
- **Upcoming xenon time-sync LIF measurement campaign**

Comparison of Global Parameters

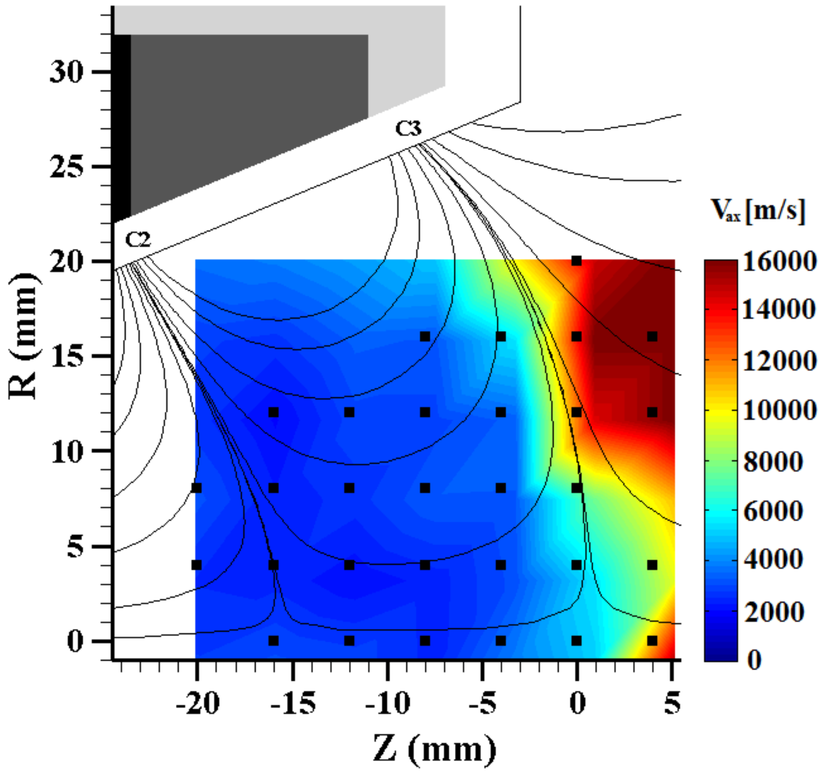
Krypton Operating Parameters (Time-Sync)

Anode Flow Rate:	12 sccm Kr
Anode Potential:	350 V
Anode Current:	0.595 A
Cathode Flow Rate:	1.5 sccm Kr
Cathode Heater:	4.7 V, 4.00 A
Cathode Keeper:	16 V, 0.500 A
Background Pressure:	1.2×10^{-5} torr

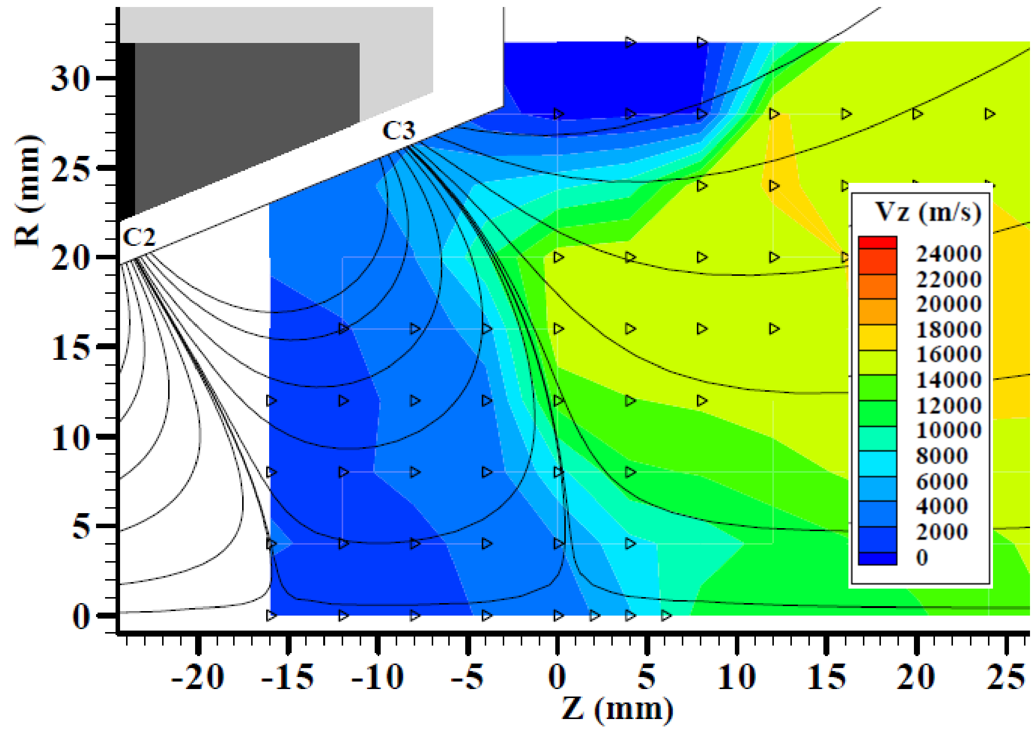
Xenon Operating Parameters (Time-Sync)

Anode Flow Rate:	8.5 sccm Xe
Anode Potential:	300 V
Anode Current:	0.49 A
Cathode Flow Rate:	1.5 sccm Xe
Cathode Heater:	4.7 V, 4.00 A
Cathode Keeper:	16 V, 0.500 A
Background Pressure:	1.2×10^{-5} torr

Time-Ave Axial Velocities: Kr vs. Xe



DCFT Operating on 12 sccm Kr, 350 V



DCFT Operating on 8.5 sccm Xe, 300V